Layered Organization in the Coastal Ocean: 4-D Assessment of Thin Layer Structure, Dynamics and Impacts

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LONG-TERM GOALS

Our long-term goal is to understand (1) the properties of densely concentrated, thin layers of planktonic biota that can occur in coastal ocean environments, (2) the interacting physical, chemical, biological and optical processes responsible for establishment, maintenance and breakdown of layers, (3) the impact of thin layers on the dynamics of plankton populations and the performance of optical sensors, and (4) how the above vary between coastal systems that differ in physical size, exposure to physical forcing, and susceptibility to episodic events.

OBJECTIVES

Our objectives for this LOCO project are (1) to understand the physical, biological, optical, chemical and acoustical properties of vertically thin horizontal layers of biota and biogenic particles in coastal oceans, and the processes responsible for the formation, maintenance and dissipation of layers; (2) to understand the spatial coherence and spatial properties of thin layers in the coastal ocean (especially in terms of optical properties), as well as the temporal durability of layers, where they occur; and (3) to use the information gleaned in the first two objectives along with data from our studies in other coastal systems to test and refine our models of thin layer dynamics (Donaghay and Osborn, 1997) and thus continue to develop the ability to predict layer formation and presence in the coastal ocean. Our primary objectives during the past 12 months of this grant have been to (1) process the raw data from the 2005 and 2006 LOCO field experiments into master data files that include all measured and derived parameters, and (2) begin to use the data to address our overall scientific objectives. Our secondary objective was to continue to publish the results of our previous work on thin layers.

APPROACH

Our approach during the 2005 and 2006 LOCO process study combined time series data from an array of our Ocean Response Coastal Analysis System (ORCAS) (Donaghay, 2004; Babin, et al, 2005) autonomous bottom-up profilers with spatial data collected over a broader area using our ship-

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deployed, high-resolution profiler. These efforts were done in close collaboration with LOCO projects led by Holliday, Hanson, Rines, Goodman, and McManus. Our efforts are discussed below along with collaborations in collecting and analyzing the data.

The first major component of our effort involved using an array of autonomous profilers to simultaneously collected temporal data on the spatial variations in vertical fine-scale physical, chemical, optical, and acoustical structure. We deployed two of our ORCAS bottom-up profilers 100 m apart in the cluster located at K1 and a third profiler at station K2 located 1 km further offshore along the cross-shelf K line. This design allowed us to sample simultaneously at two different spatial scales. The profilers collected centimeter-resolution profiles at least once an hour of temperature, salinity, depth, oxygen, spectral absorption, spectral attenuation, spectral scattering, backscatter at 532 nm, chlorophyll a fluorescence, and CDOM fluorescence. Our ORCAS profilers at K1 South and K2 had a Nortek ADV (Acoustic Doppler Velocity meter) for simultaneously measuring centimeter- scale currents and turbulence. Our ORCAS profiler at K1 North had the same suite of sensors as the other profilers except that had additional sensors for nutrients (a SubChem Systems autonomous nutrient analyzer provided by Hanson) and light (Satlantic OCR-4 downwelling light sensor). In addition, the multi-spectral WET Labs ac-9 was replaced on this profiler with a WET Labs ac-s hyper-spectral absorption and attenuation and meter. Other time series sensors at each of these locations included a TAPS multi-frequency acoustics zooplankton profiler deployed by Holliday, an ADCP for measuring currents and current shear once a minute with 25-50 cm resolution (deployed by Holliday or McManus) and a thermister string for measuring internal waves (deployed by Holliday or McManus). Data from our array of profilers was radioed to shore at the end of each profile. Near-real time preliminary analysis of this data was used to quantify temporal changes in physical, chemical and optical structure and look for the occurrence and extent of thin optical layers. These results were communicated to the other PIs by e-mail and used to guide ship-based sampling efforts. Analyses of these data during this next year will be used to (1) detect the presence, intensity, thickness, temporal persistence, and spatial coherence of thin optical and acoustical layers, (2) quantify their optical and acoustical characteristics, and (3) quantify their association with physical, chemical and biological structures and processes that have been hypothesized to control thin layer dynamics.

The second major component of our effort involved using the R.V. Shana Rae to periodically collect ship-deployed high-resolution profiles needed to (1) validate the measurements made by the autonomous optical profilers, (2) characterize the larger scale spatial variability in the fine-scale structure detected by the array, and (3) further characterize the inherent optical properties of thin layers detected by the array. Our high-resolution profiler had the same sensor suite as the bottom-up IOP profilers plus a PAR light sensor, a second WET Labs ac-9 with a 0.2 micron pre-filter for measuring spectral absorption by dissolved substances, a pair of WET Labs ac-s high-spectral resolution absorption and attenuation meters (one without and 1 with a 4 micron pre-filter to measure absorption, attenuation and scattering by small particles for spectral characterization of particulate and dissolved material), and a SubChem analyzer (provided by Hanson - see his report) for measuring fine-scale nutrient structure. We plan to combine these data with data from the array to define (1) the spatial variability along-shore and cross-shore in layer thickness, intensity, optical characteristics, and biological composition, and (2) the association of these changes with changes in the physical, chemical and biological structures and processes that have been hypothesized to control thin layer dynamics. We also plan to eventually combine these data with similar physical and optical data that Cowles collected in deeper water to determine the along-shore and cross-shore dimensions of any thin layers that extend outside the local region that we plan to sample.

The third component of our effort involved using the R.V. Shana Rae to periodically collect plankton samples from inside and outside thin layers. Real-time data from our high-resolution profiler was used to guide the collection of plankton samples from inside and outside thin optical layers using a rosette bottle sampler. Rines (see her LOCO report) is using these samples to identify the biological composition of the plankton. In addition, we collaborated with Holliday in using real-time data from his TAPS array to guide collection of net samples needed to identify the composition of zooplankton present and collect photographic images of zooplankton needed for inversion of the acoustic data on zooplankton distributions (as planned by Holliday). We also periodically towed our newly acquired Laser Optical Plankton Counter (LOPC) along the K line to collect optical data on the abundance, size and shape of the zooplankton that were being measured by Holliday's TAPS at K1 and K2 and by the multi-frequency acoustic profilers deployed from the Shana Rea by Benoit-Bird.

WORK COMPLETED

Published papers on earlier work and its implications. We have published two papers this year and have a third paper in press. The first paper (Cheriton, et al, 2008) examines the spatial patterns of formation of thin acoustic layers along the US west coast. The second paper (McManus et al, 2008) discusses criptic layers of harmful algae in Monterey Bay. The third paper (Churnside and Donaghay, in press) examines the frequency of occurrence, spatial extent, and characteristics of thin optical backscattering layers in coastal and open ocean areas of the North Pacific and North Atlantic using 80,000 kilometers of high vertical and horizontal resolution optical backscatter data collected by James Churnside (NOAA) during tests of an airborne LIDAR that he developed to survey epipelagic fish.

Development of a procedure for automated detection and characterization of thin layers. We have completed the development and testing of a Matlab© program that utilizes a rigorous mathematical approach to auto-detect and characterize thin layers found in large sets of vertical profiles collected by our ORCAS autonomous profilers. The program uses a derivative technique to detect thin layers, define the centroid and upper and lower limits of the layer, and then calculate the intensity and thickness of the layer. The program sorts the layers based on intensity and thickness so we can select those that exceed our criteria for being "thin layers". Finally, the program uses the full suite of bio-optical, physical and chemical measurements to characterize the thin layer, differentiate it from the water at the upper and lower bounds of the layer, and evaluate the layers contribution to the integrated properties of the water column. After extensively testing the program, we have applied it to the more than 2000 ORCAS profiles collected in Monterey Bay during the 2002 test deployment and during LOCO experiments conducted in 2005 and 2006. We have also applied the program to the AUV data collected by John Ryan during the LOCO 2005 experiment so that we could combine the two data sets to look at the temporal and spatial extent of thin layers.

Presentation of LOCO results at international meetings and workshops. First, Donaghay co-chaired with Holliday and McManus a special session on thin layers at the 2008 Ocean Sciences meeting. Donaghay gave a talk at the meeting and Sullivan presented a poster on our LOCO research. Second, Donaghay and Sullivan gave presentations at the 2008 LOCO workshop. Third, Donaghay presented an invited paper on the ORCAS profilers at the 2008 NSF profiler workshop.

Editing the special issue of Continental Shelf Research. Sullivan and Donaghay are co-editing (with Margaret McManus) a special issue dedicated to the ONR LOCO experiment. We have worked with

Jim Eckman and our colleagues in the LOCO program to design a special issue, get it accepted by the journal, establish a time table for manuscript submission (December 1, 2008) and then encourage the timely completion of the papers.

Development of papers based on the LOCO experiments. We have 1 paper in press and 3 manuscripts intended for submission to the LOCO special issue of Continental Shelf Research (CSR). These manuscripts are based both on our own data and our collaborations with other LOCO investigators. First, we have a paper in press with Holliday (Holliday et al, in press) on the interactions between thin layers formed by migrating phytoplankton and zooplankton. Second, we have completed a manuscript on the patterns of occurrence and characteristics of thin layers measured by the ORCAS profilers during 2002, 2005 and 2006 (Sullivan, et al, CSR ms.). This manuscript has been circulated to the other LOCO investigators. Third, we are developing a manuscript with Rines, Hanson, and Holliday on the role of swimming behavior and bio-physical interactions in controlling thin layer formation and dynamics during the 2005 and 2006 LOCO experiments (Donaghay, et al, CSR ms). Fourth, Sullivan is collaborating with Ryan in developing a manuscript that combines the MBARI AUV and ORCAS data to assess the temporal and spatial extent of thin layers (Ryan, et al, CSR ms).

RESULTS

Evaluation of the ability of the derivative program to detect and characterize thin layers. We have evaluated the ability of our Matlab© program to detect and characterize thin layers by comparing its output to the underlying data at each step in the processing (Figure 1). As illustrated in Figure 1a, the program does a good job of using derivative analysis to detect the location of the thin layer and its upper and lower extent despite the high levels of micro-scale variability in the raw data and the differences in average chlorophyll a concentrations above and below the thin layer. One of the keys to this success was our use of the derivative analysis of the smoothed chlorophyll a data solely for the purpose of identifying the centroid and upper and lower bounds of the thin layer. This allowed us to perform all subsequent calculations on the full resolution data (Figure 1b, c) thus minimizing artifacts that can be created by conducting such analyses on smoothed data. Our evaluation of the performance of this program on the more than 2000 individual ORCAS profiles collected in Monterey Bay indicates the program has several advantages over the approaches we have previously developed for analyzing high-resolution bio-optical profiles collected by ship-deployed systems (Dekshenieks, et al, 2002). First, the program allows us to mathematically define the upper and lower bounds of the thin layer at its base (Figure 1c). This allows us to calculate background concentrations at the centroid of the thin layer thus providing a quantitative way to estimate the intensity of the thin layer even in cases where there is a substantial background (as frequently occurs when motile phytoplankton periodically form

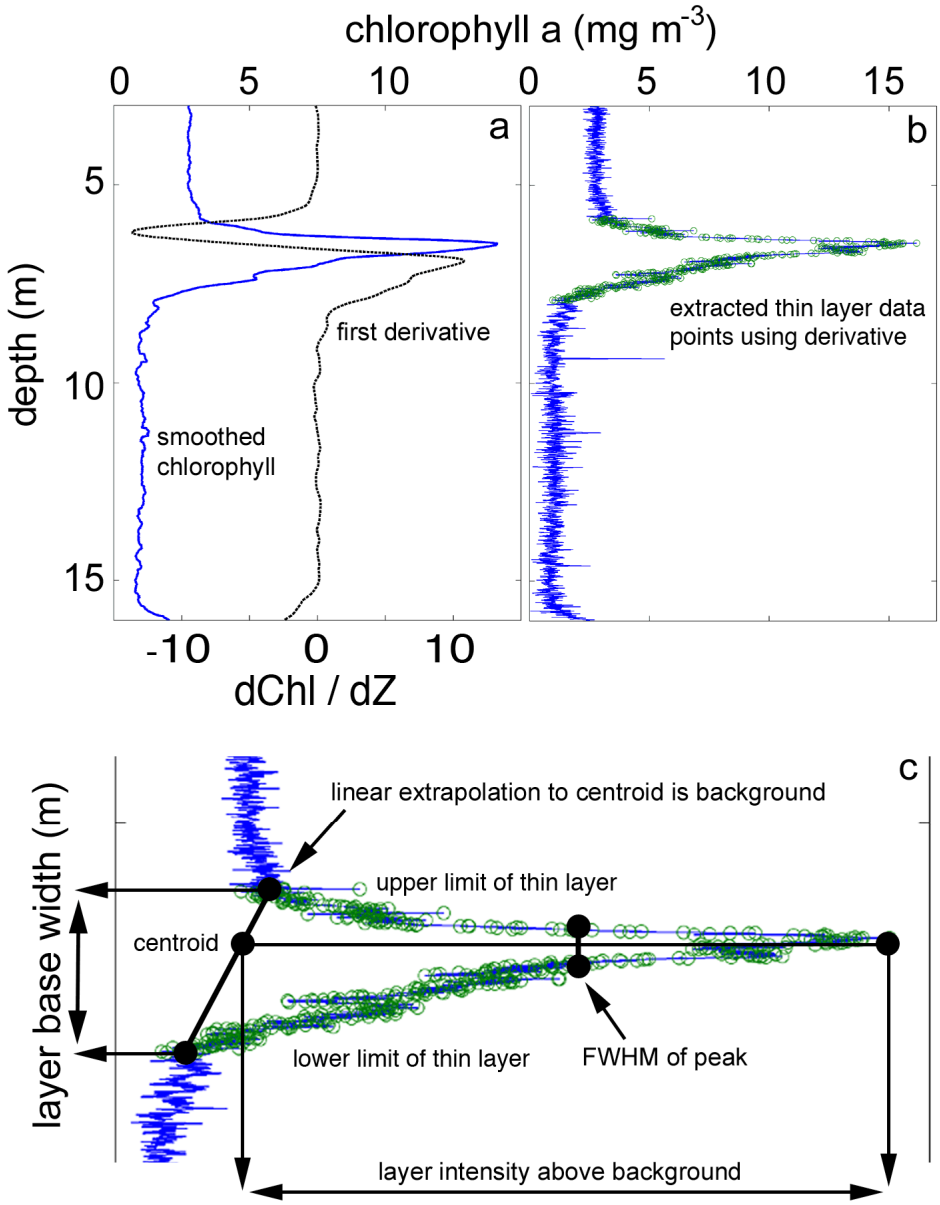

Figure 1. Detection and characterization of thin layers using automated derivative analysis. The figure shows (a) an example of a smoothed vertical profile of chlorophyll and its first derivative, (b) the same chlorophyll data at full resolution (blue points) and extracted thin layer data points using the derivative methods (green points), and (c) the centroid, FWHM, and thin layer upper and lower limit metrics (solid circles) used to describe thin layer characteristics from the extracted data.

thin layers on top of layers of non-motile phytoplankton and detritus). Second, the ability of the program to extract data at the depths of the centroid of the layer, the depths of upper and lower bounds of the layer, and the depths of the upper and lower bounds of the layer at its midpoint (e.g., solid circles in Figure 1c) provides the quantitative data needed to compare the characteristics of the thin layer (and its environment) at its centroid to those same characteristics measured at several points above and below the center of the layer. This capability has proven invaluable in our efforts both the characterize the physical, chemical, optical and acoustical properties of thin layers, but also to our

efforts to use these data to test models of thin layer dynamics and impacts (Sullivan, et al, CSR ms; Donaghay, et al, CSR ms). Third, the ability of the program to sort layers based on their intensity and thickness (FWHM) allows us to quantify the median and range of both parameters in any given data set and then use this information to select criteria for deciding what constitutes a "thin layer". This greatly facilitates evaluating alternative definitions of thin layers, and then selecting the most appropriate one given the characteristics of the environment and sensors. Fourth, the ability of the program to define upper and lower limits of the thin layer allows us to calculate the integrated value of thin layer characteristics. This gives a way to estimate the impact of thin layers on a variety of processes and the performance of remote sensing systems. (Sullivan, et al, CSR ms).

Characteristics of thin layers observed during 2005 and 2006 LOCO Monterey Bay experiments. We have used the thin layer detection program to evaluate all the ORCAS time-series profiles collected in 2002, 2005 and 2006. Our analysis of the over 2000 profiles collected during this period indicates that the median vertical thickness for all Monterey Bay layers was ~ 1.2 m with ~ 2 times the background chlorophyll value and a base-width of ~ 2.9 m. Given the 1x intensity criteria, thin layers were present in the water column 87% of the time in 2002, 56% of the time in 2005 and 21% of the time in 2006. The median integrated chlorophyll concentration within thin layers was found to be approximately 47% of the total water column chlorophyll in 2002, 41% in 2005, and 33% in 2006. The contribution of thin layers to total integrated chlorophyll a varied over a wide range in both years with most values ranging between 10 to 90% in 2005 (Figure 2a) and 10 and 80% in 2006 (Figure 2b). These

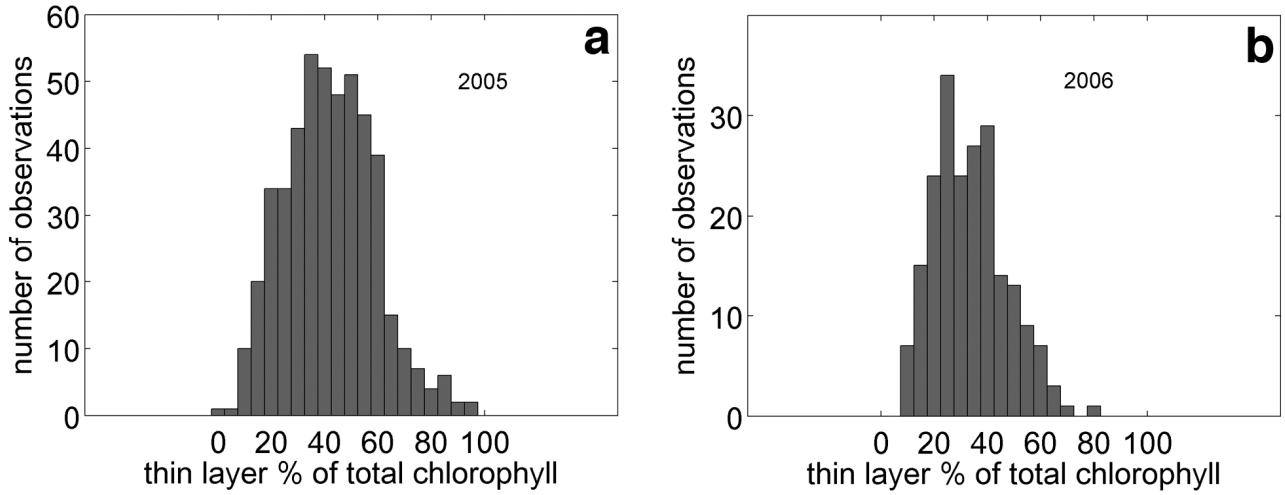

Figure 2. The integrated chlorophyll concentration of thin layers as a percentage of the total integrated water column chlorophyll concentration for 2005 (a) and 2006 (b). These figures were generated using an intensity criteria of 1x background and a FWHM thickness criteria of less than 3 m. The figure shows that while the thin layers as a percent of total integrated water column varied over a wide range in both years (with most values ranging from 10 to 80%), the median (41%) and maximum (~95%) values were slightly higher in 2005 than in 2006 (median of 33% and maximum of ~80%).

contributions to total integrated biomass are quite impressive given that they occurred in a vertical depth range that was only ~ 10% of the total water column depth. These results reinforce the importance of understanding thin layer dynamics and its impacts on water column optics, carbon and

food reservoirs, water column primary productivity and the successful feeding or foraging of herbivores.

Impact of thin layers of motile phytoplankton on fine-scale structure of optical properties. One of our objectives in this project was to evaluate the impact of thin layers on the optical characteristics of the water column. We were particularly interested in testing whether formation of intense thin layers by vertically migrating dinoflagellates (such as those formed at depth each night in 2005 by the dinoflagellate *Akashiwo sanguinea*) would be reflected in the other optical parameters we measured to the same extent that they were in chlorophyll a. To test this idea, we plotted the fine-scale vertical structure of a variety of measured and derived optical properties and compared the magnitudes and directions of the resulting changes in structure (Figure 3). As illustrated in Figure 3, it is quite clear that

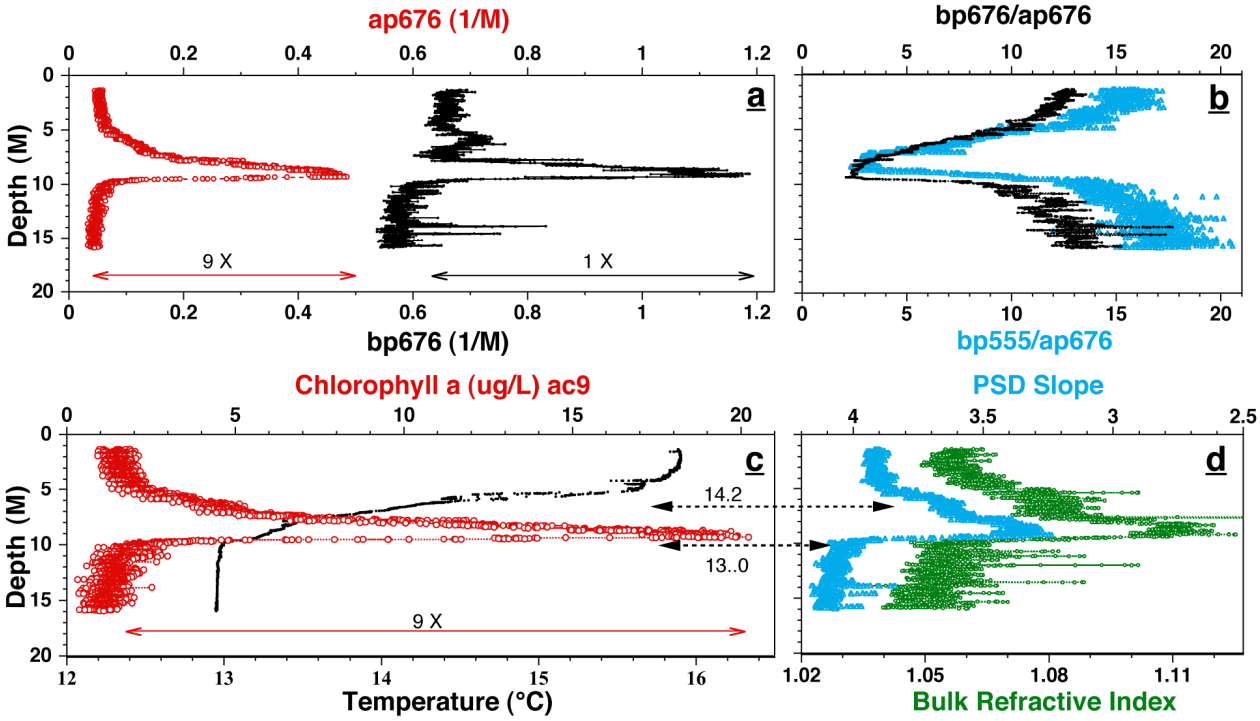

Figure 3. Impact of thin layer formation by the migrating dinoflagelate Akashiwo sanguinea on the fine-scale vertical structure of (a) absorption at 676 nm (red dots) and scattering at 676 nm (black dots), (b) ratios of scattering at 676 nm to absorption at 676 nm (black dots) and scattering at 555 nm to absorption at 676 nm (blue dots), (c) chlorophyll a estimated from ac-9 data (red circles) relative to temperature (black dots), and (d) inversion model estimates of PSD slope (cyan dots) and bulk refractive index (green dots). The location of zooplankton layers at 14.2 °C and 13°C are denoted by the dashed arrows in Figure 3c,d. The figure shows that the thin layer of A. sanguinea at the base of the thermocline (e.g., at 9 m) is not only sufficiently intense to be detected as a thin layer in all three optical estimators of particulate biomass (e.g., absorption, scattering, and chlorophyll a), it is also has sufficiently different optical characteristics to be detected as a maxima in the bulk refractive index and as minima in and PSD slope and the IOP ratios bp676/apr676 and bp555/apr676.

the thin layer of *A. sanguinea* that formed at the at the base of the thermocline (e.g., at 9 m) is not only sufficiently intense to be detected as a thin layer in all three optical estimators of particulate biomass (e.g., absorption, scattering, and chlorophyll a) (Figure 3a,c), but that it is also has sufficiently different optical characteristics to be detected as a maxima in the bulk refractive index (Figure 3d) and as minima in and PSD slope (Figure 3d) and as a minima in the IOP ratios b676/a676 and b555/ap676 (Figure 3b). Comparison of the absorption and scattering fine-scale profiles (Figure 3a,b) indicates that the differences in IOP ratios (Figure 3b) strongly reflect both the much higher scattering above and below thin layer (and the resulting 9 fold difference in thin layer intensity as measured by absorption and scattering) as well as the occurrence of small secondary peaks in scattering at 6 and 15 m that do not appear in the absorption profile. This much higher level of background scattering is qualitatively consistent with the microscopic observation by Rines (see her report) that while the thin layer was dominated by *A. sanguinea* (a 40 by 70 micron dinoflagellate packed with chloroplasts that should have high absoption relative to scattering), the rest of the water column was dominated by chains of thin, chlorophyll deficient diatoms that should have low absorption relative to scattering. Although consistent with the microscopy, the magnitude of the effect is impressive. For example, the changes in scattering to absorption ratios varied by a factor of 6 (ranging from 2 in the layer to 13 in the surface and deep waters). This effect is also obvious in profiles of PSD slope (Boss et al, 2001) and bulk refractive index (Twardowski, et al, 2001) where the observed variation between the layer and surrounding waters represents more than 50% of the dynamic range reported by Sullivan et al (2005) in his survey of 6 highly diverse coastal environments. In summary, results such as these have convinced us that thin layer formation by migrating dinoflagellates not only alters the fine scale the quantitative and qualitative characteristics of the water column, but also that these changes in optical characteristics can be powerful tools for tracking such migrations and understanding the physiological conditions of the different populations involved. (e.g., both the non-motile and immigrating species).

Impact of phytoplankton thin layer formation on migration behavior of zooplankton: Another one of our objectives in this project was to evaluate the impact of thin layer formation by phytoplankton on the vertical migration of zooplankton. As part of our ongoing collaboration with D.V. Holliday, we have combined our time series estimates of changes in phytoplankton distributions made by our ORCAS profilers with the his high frequency (1per minute) TAPS acoustic time series estimates of fine-scale zooplankton distributions. Although one might expect the vertically migrating zooplankton to aggregate in the thin layer of dinoflagellates, instead the zooplankton migrated down and formed thin layers just above (at 14.2 °C) and just below (at 13 °C) the thin optical layer of *A. sanguinea* described above (as denoted by the arrows labeled 14.2 and 13 in Figure 3c,d). This is really quite remarkable give that the zooplankton avoided a layer composed of high concentrations (20 ug/L chlorophyll a) of a large dinoflagellate for regions of much lower biomass (2 ug/L chlorophyll a) dominated by diatoms that appeared to be in poor physiological condition. This result has several very important implications. First, it clearly demonstrates that thin layer formation by phytoplankton does necessarily result in increased losses to grazing and thus layer dissipation. In this case, the pattern of thin layer formation by migrating zooplankton should lead to increased grazing pressure just above and below the thin layer thus resulting in thin layer intensification. Second, it demonstrates that thin layer formation by phytoplankton does necessarily result in increased transfer to higher trophic levels that might be expected from the dramatically higher biomass (Holliday, et al, in press).

IMPACT/APPLICATION

One of the central assumptions in biological oceanography has been that small scale mixing processes in the upper ocean are sufficiently strong and equal in all directions that sub-meter scale biological, chemical and optical structures will be rapidly dispersed and thus can be ignored in both sampling and modeling upper ocean dynamics. Results from our measurements of finescale structure in East Sound (WA), Monterey Bay (CA), the Gulf of Mexico, and off the west coast of Ireland clearly indicate that this assumption is frequently incorrect. These measurements also indicate that the accurate assessment of occurrence, intensity, spatial extent, and temporal persistence of thin optical layers requires centimeter-scale sampling. Our field results and theoretical analyses indicate that biological-physical, biological-chemical and biological-biological interactions occurring at these scales may control not only the development of blooms of toxic and/or bioluminescent phytoplankton, but also the extent to which zooplankton are able to exploit phytoplankton production. Equally importantly, collaborative analysis of the data with experts in optics indicates that fine-scale biological layers can become sufficiently intense at times to alter the performance of optical and acoustical sensors in coastal waters. These analyses also suggest that our bottom-up profiling systems have considerable potential for increasing our understanding biological dynamics and improving our interpretation of optical and acoustic data collected by other platforms.

TRANSITIONS

Our ORCAS profiler technology has now been successfully transitioned to four different groups through our collaborative efforts to commercialize the technology with WET Labs. First, Dr. Benjamin Cray (NUWC) has purchased and successfully deployed a modified Mini-AMP version of the profiler equipped with a CTD, ADV and an array of advanced acoustic sensors. Second, Jim Sullivan has worked with WET Labs in deploying an advanced optics version of the mini-AMP profiler during ONR's OASIS experiment off Martha's Vinyard in September 2007. Third, we have collaborated with WET Labs and Jack Barth (OSU) in developing an NSF funded version of the profiler suitable for extended deployment on the Oregon shelf. Fourth, NOAA has purchased and successfully deployed a WET Labs Mini-AMP profiler for use in one of its programs in Chesapeake Bay.

We have also continued out efforts to transition the optical calibration and data processing techniques we have developed for the WET Labs ac-9 and ac-s (Sullivan, et al, 2006). During this past year, we have continued to work with WET Labs to transition the data processing techniques into their software.

RELATED PROJECTS

This LOCO project has been developed in close collaboration with Van Holliday (URI/BAE Systems) and a core group of independent investigators that include Jan Rines (URI), Louis Goodman (SMAST), Edward Levine (NUWC), Alfred Hanson (SubChem Systems), Margaret McManus (UH), and Timothy Cowles (OSU). We have collaborated with these investigators for several years. This year we have worked closely with Goodman in the analysis of the ADV and other physical data collected during the LOCO experiments. We have shared data sets with Goodman and Sullivan has worked closely with him in designing our approach to analyzing the turbulence data from the ADV. We have also work closely with Hanson in analyzing the nutrient data collected by our autonomous ORCAS IOPC profiler and ship-deployed Hi-Res profiler.

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